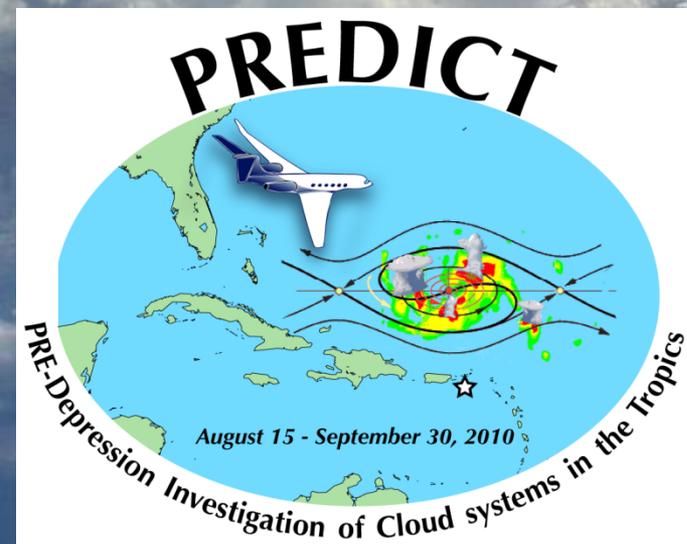
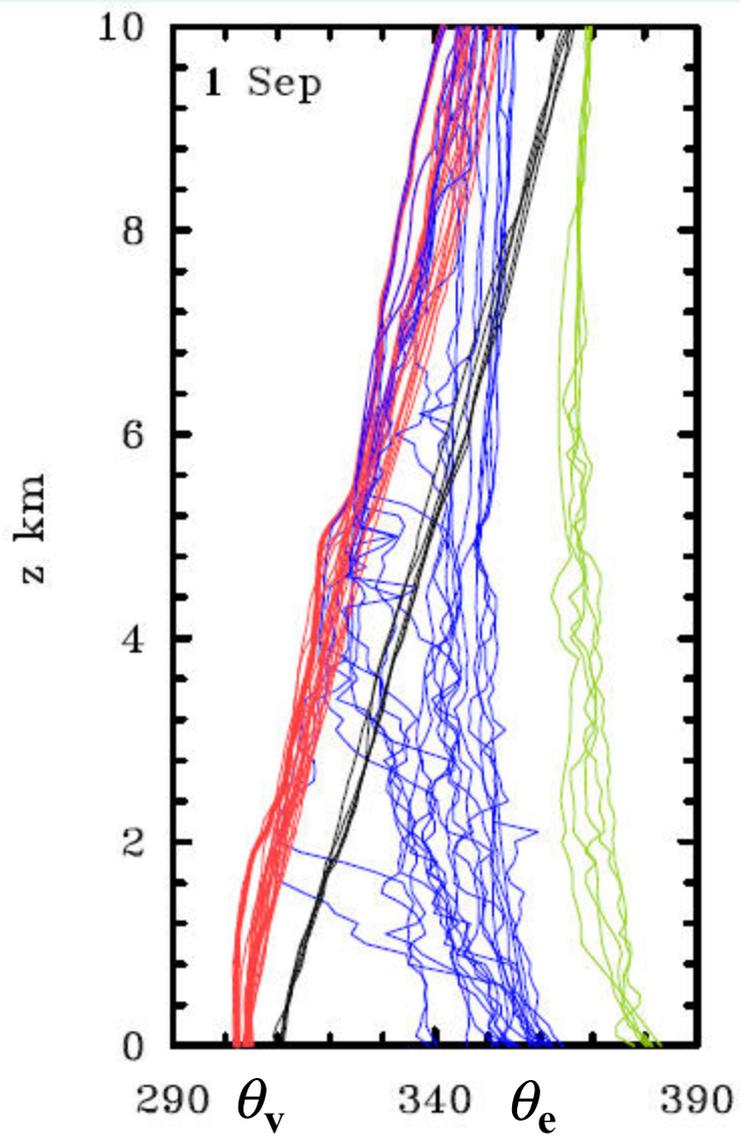


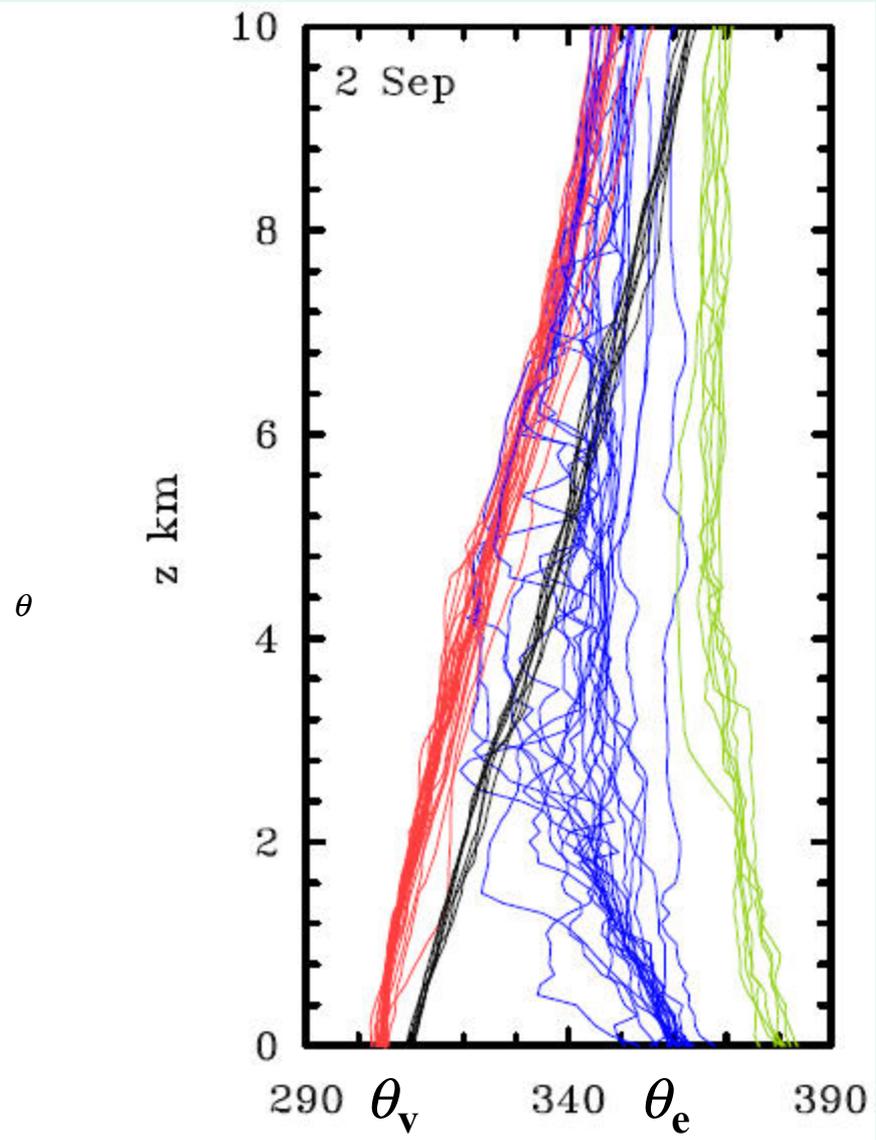
# Insights from PREDICT/GRIP



Work presented here in collaboration with: Roger Smith, Jun Zhang, Mark Boothe, Blake Rutherford and the PREDICT/GRIP teams.



(a)



(b)

$$\theta_e = \theta \exp\left(\frac{Lr_v}{c_p T}\right) \quad \rightarrow$$

$$\Delta\theta_e = \Delta\theta + \frac{L}{c_p \pi} \Delta r_v, \quad (1)$$

put  $r_v = RH r_v^*$

$$\Delta\theta_e = \Delta\theta + \underbrace{\frac{L}{c_p \pi} RH \times \Delta r_v^*}_{\Delta\theta_{e2}} + \underbrace{\frac{L}{c_p \pi} r_v^* \times \Delta RH}_{\Delta\theta_{e3}}, \quad (2)$$

$\Delta\theta_{e1}$

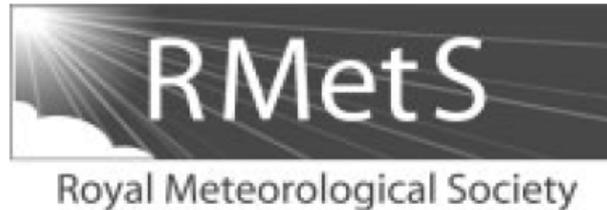
$\Delta\theta_{e2}$

$\Delta\theta_{e3}$

The premise of the air-sea interaction model of Malkus and Riehl (1960) and E86 (and later refinements) is that isothermal expansion, by itself (i.e.  $\Delta\theta_{e3} = 0$ ), cannot provide a sufficient increment in  $\theta_e$  to support a strong hurricane. In other words, latent heat transfer over and above that required to maintain the relative humidity in the presence of isothermal expansion is assumed to be crucial for storm maintenance.

**What do observations tell us?**

In press



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# How important is the isothermal expansion effect to elevating equivalent potential temperature in the hurricane inner-core?

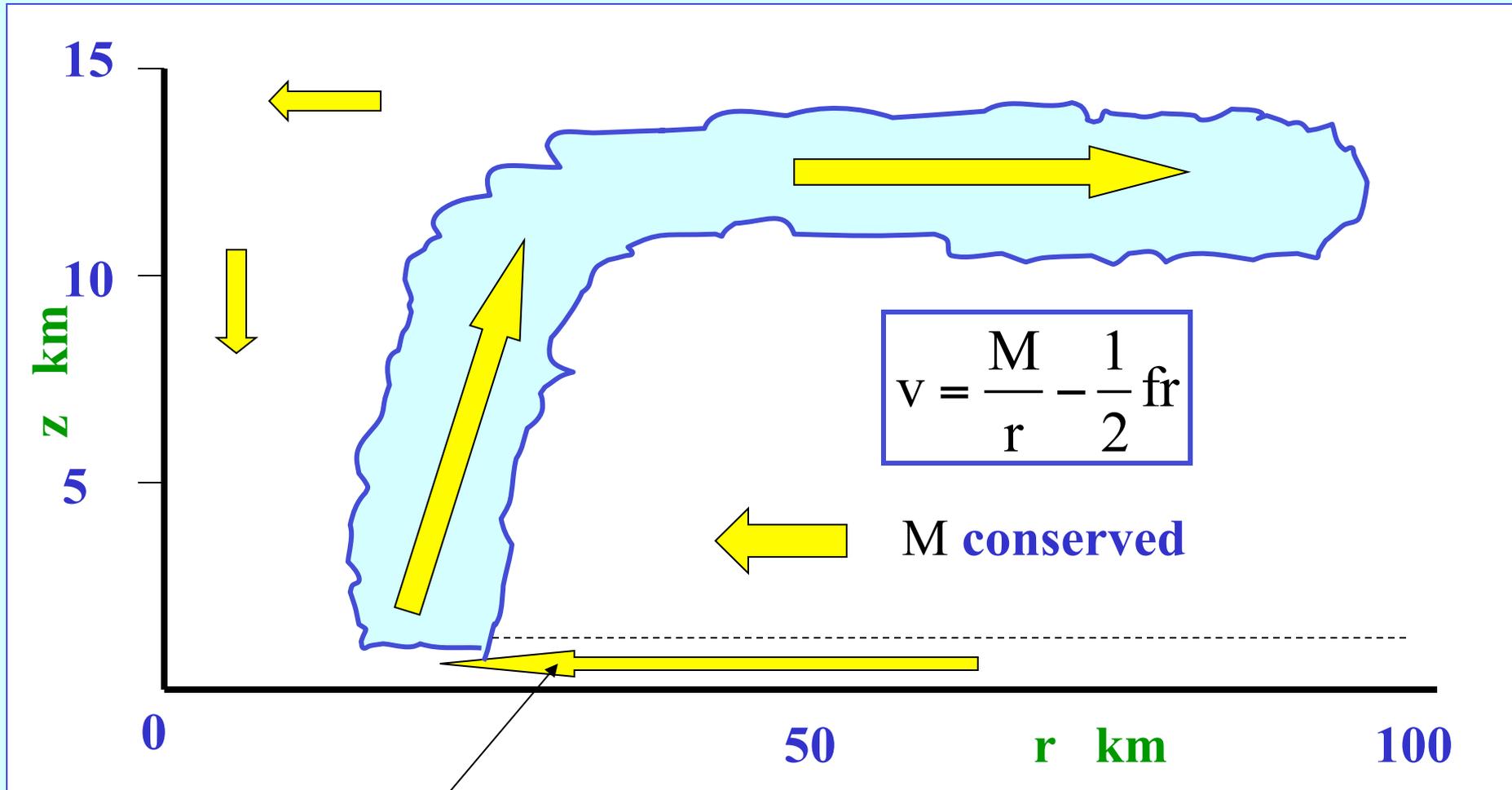
Roger K. Smith<sup>a</sup> \* and Michael T. Montgomery<sup>b</sup>

<sup>a</sup> *Meteorological Institute, University of Munich, Munich, Germany*

<sup>b</sup> *Dept. of Meteorology, Naval Postgraduate School, Monterey, CA*

\*Correspondence to: Prof. Roger K. Smith, Meteorological Institute, Ludwig-Maximilians University of Munich, Theresienstr. 37, 80333 Munich, Germany. E-mail: roger.smith@lmu.de

# Revised view of intensification: two mechanisms



M reduced by friction, but strong convergence  $\rightarrow$  small  $r$

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# Observations and interpretations of the low-level structure of Hurricane Earl (2010)

Michael T. Montgomery<sup>a\*</sup>, Jun A. Zhang<sup>b</sup>, and Roger K. Smith<sup>c</sup>

<sup>a</sup> *Dept. of Meteorology, Naval Postgraduate School, Monterey, CA, USA*

<sup>b</sup> *NOAA Hurricane Research Division, Miami, FL, USA*

<sup>c</sup> *Meteorological Institute, University of Munich, Munich, Germany*

\*Correspondence to: Prof. Michael T. Montgomery, Dept. of Meteorology, Naval Postgraduate School, Monterey, CA 93943, USA. E-mail: mtmontgo@nps.edu

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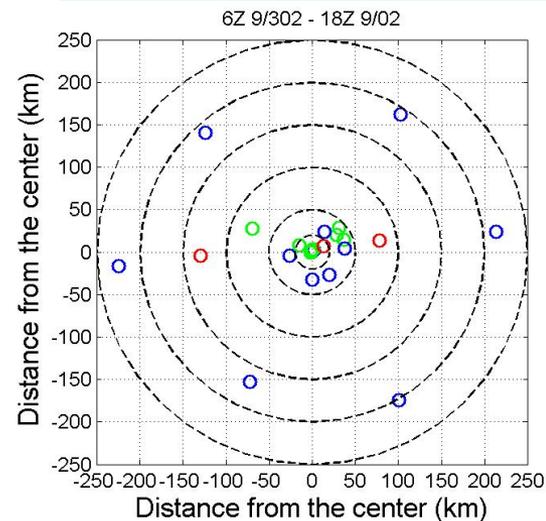
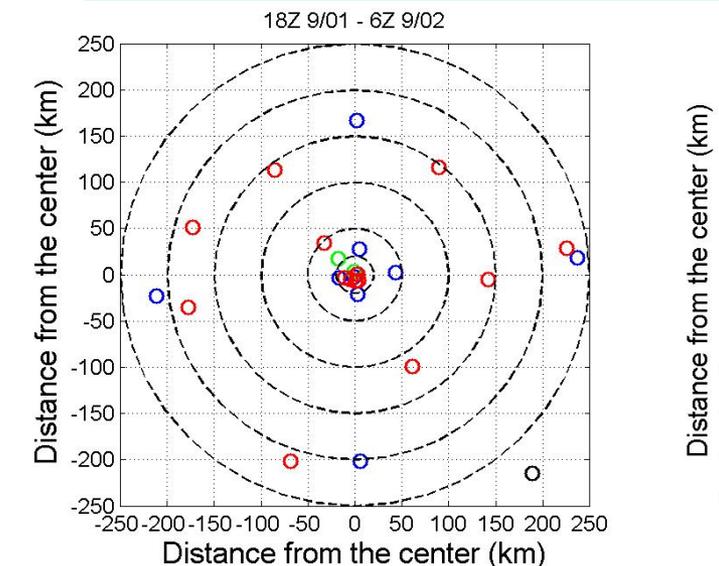
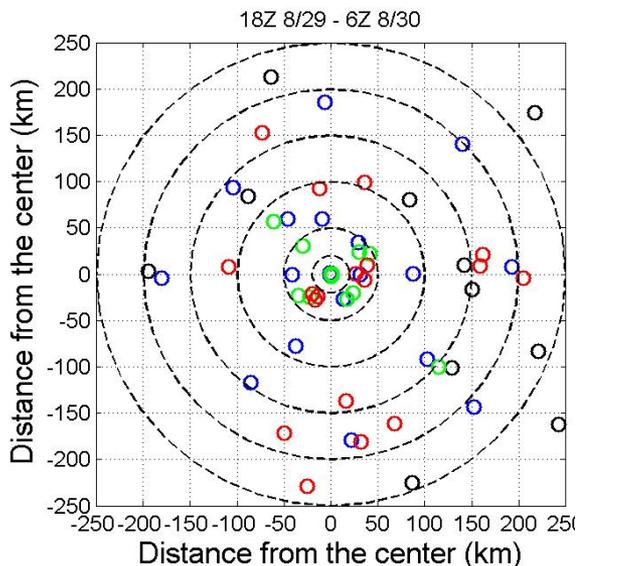
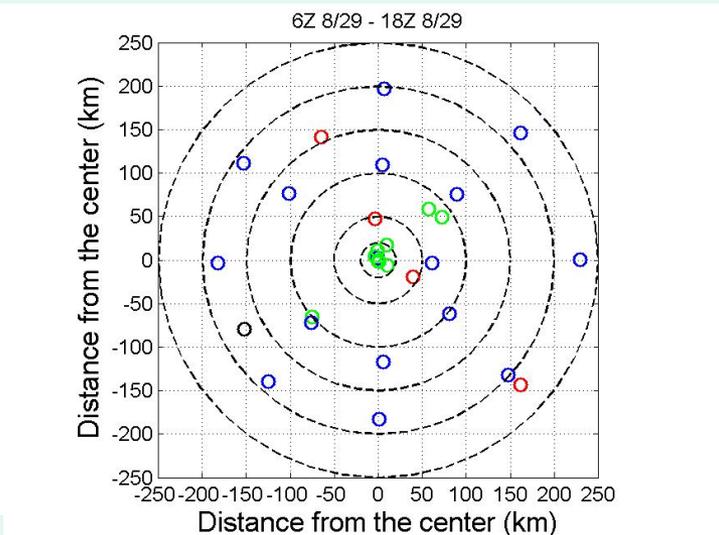
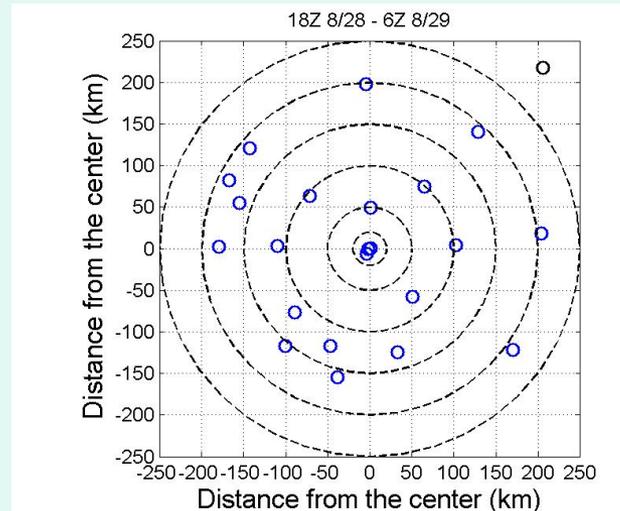
**We examine aspects of the kinematic and thermodynamic structure of Atlantic Hurricane Earl (2010) during four days of intensive measurements based on airborne dropwindsondes released from the upper troposphere during the National Aeronautics and Space Administration (NASA), Genesis and Rapid Intensification Processes (GRIP) experiment.**

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*Key Words:* Hurricanes, thermodynamic structure, surface fluxes, GRIP

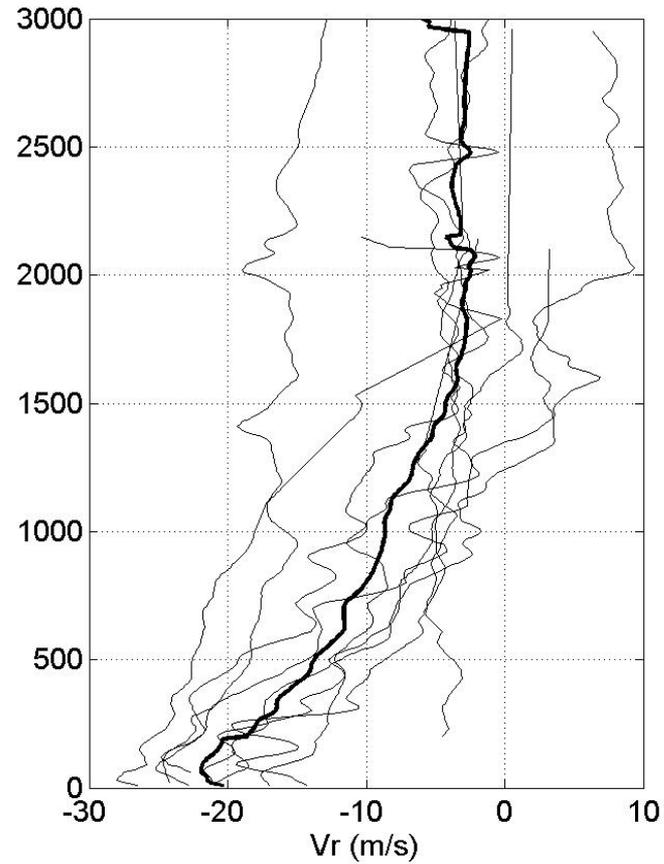
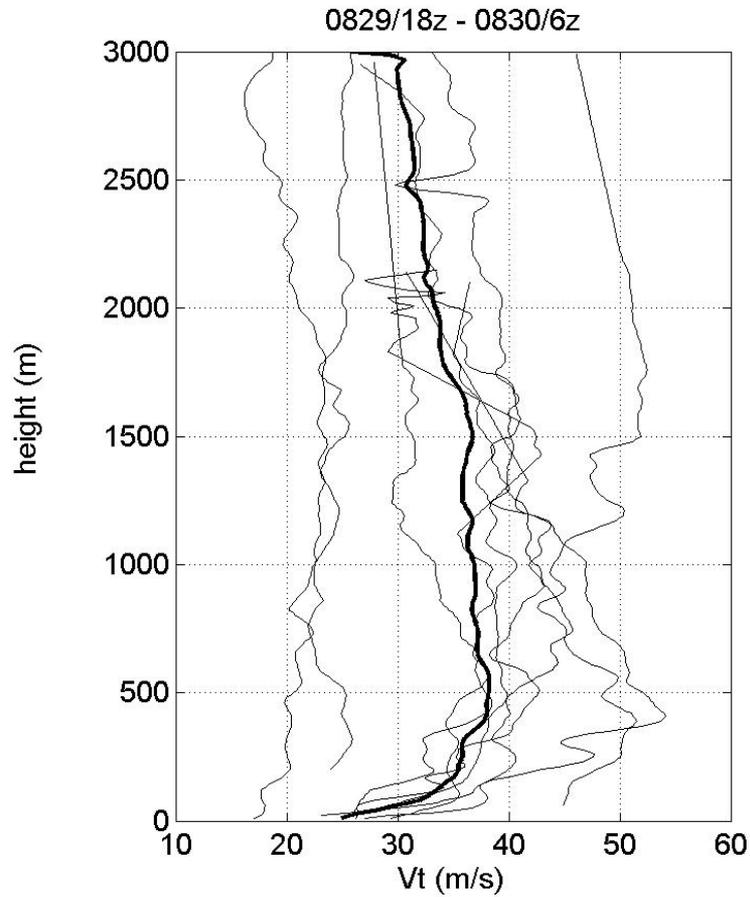
# Dropsonde data spatial coverage

*Blue, P-3*  
*Red, DC-8*  
*Green, C-130*  
*Black, G-IV*



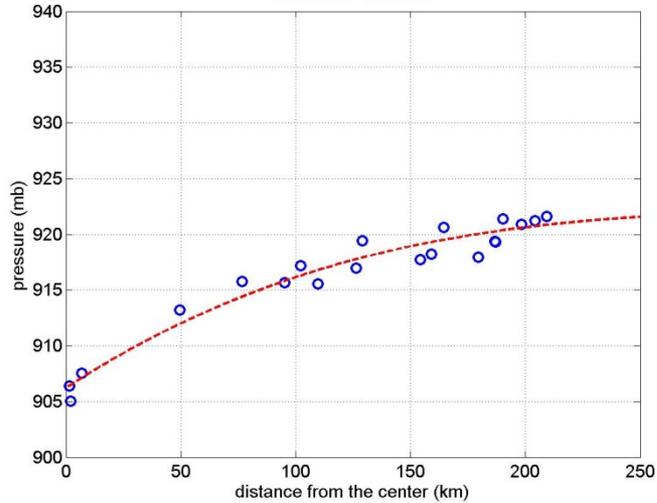
data are grouped within 12 hour period centered on 0 Z and 12 Z  
of each day

# Vertical profiles of $V_t$ and $V_r$ for Period 3 (0829/18Z – 0830/6Z)

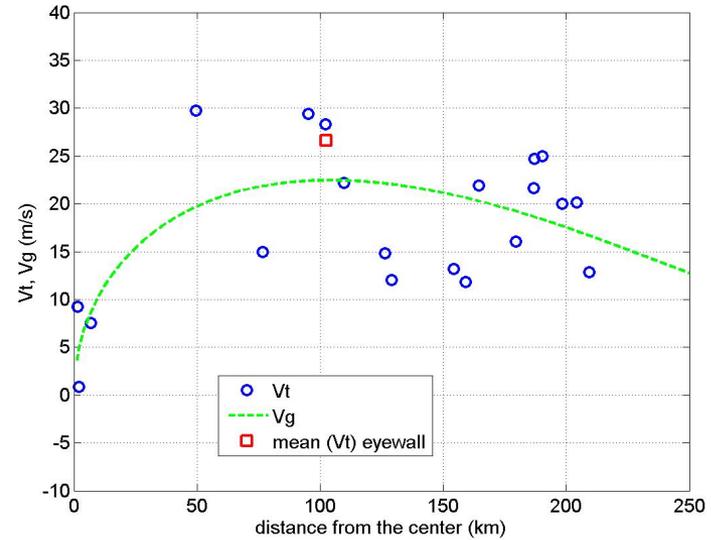


# Gradient wind at height of max Vt for periods 1 and 3 (Aug. 28 and 29)

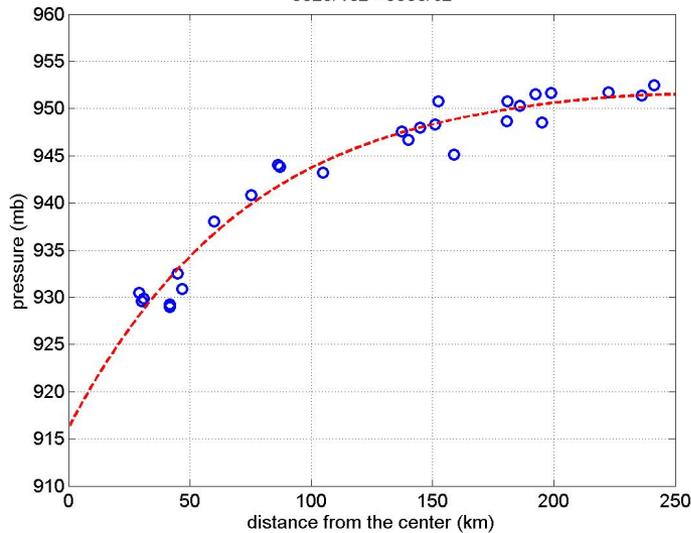
0828/18z - 0829/6z



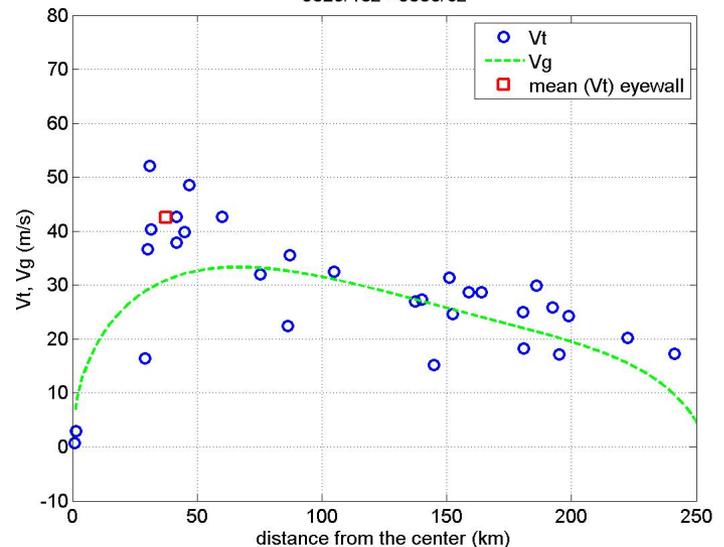
0828/18z - 0829/6z



0829/18z - 0830/6z



0829/18z - 0830/6z



# Lessons learned Re low-level intensification of Earl (2010)

- Maximum mean  $V_t$  is within the frictional boundary layer during the spin up phase
- Supergradient mean  $V_t$  was found in the eyewall region at the height of maximum  $V_t$  during both spin up and maturity
- These findings support in part the new intensification paradigm in which HBL plays an active role in dynamics

# How do tropical cyclones form?

For a cyclone to form several preconditions must be met:

1. Warm ocean waters (of at least 26.5°C) throughout a sufficient depth (unknown how deep, but at least on the order of 50 m). Warm waters are necessary to fuel the engine of the tropical cyclone.
2. An atmosphere which cools fast enough with height (is "baroclinic") such that it encourages thunderstorm activity. It is the thunderstorm activity that liberates the heat stored in the ocean waters to be liberated for the tropical cyclone.
3. Relatively moist layers near the mid-troposphere. Dry mid levels are not conducive for allowing the continuing development of thunderstorm activity.
4. A minimum distance of around 500 km from the equator. Some of the earth's spin (Coriolis force) is needed to maintain the structure of the system. (Systems can form closer to the equator but it's a rare occurrence).
5. A pre-existing disturbance at the surface with sufficient spin (vorticity) and inflow (convergence). These conditions cannot be generated spontaneously. To develop, they require a weakly organised system with sizeable spin and low level inflow.
6. Little change in the wind with height (low vertical wind shear, i.e. less than 40 km/h from surface to tropopause). Large values of wind shear tend to disrupt the organisation of the thunderstorms that are important to the inner part of a cyclone.

Having these conditions met is necessary, but not sufficient as many disturbances that appear to have favourable conditions do not develop.

**So: how do they form? !!!**

# THE PRE-DEPRESSION INVESTIGATION OF CLOUD-SYSTEMS IN THE TROPICS (PREDICT) EXPERIMENT

Scientific Basis, New Analysis Tools, and Some First Results

BY MICHAEL T. MONTGOMERY, CHRISTOPHER DAVIS, TIMOTHY DUNKERTON, ZHUO WANG, CHRISTOPHER VELDEN, RYAN TORN, SHARANYA J. MAJUMDAR, FUQING ZHANG, ROGER K. SMITH, LANCE BOSART, MICHAEL M. BELL, JENNIFER S. HAASE, ANDREW HEYMSFIELD, JORGEN JENSEN, TERESA CAMPOS, AND MARK A. BOOTHE

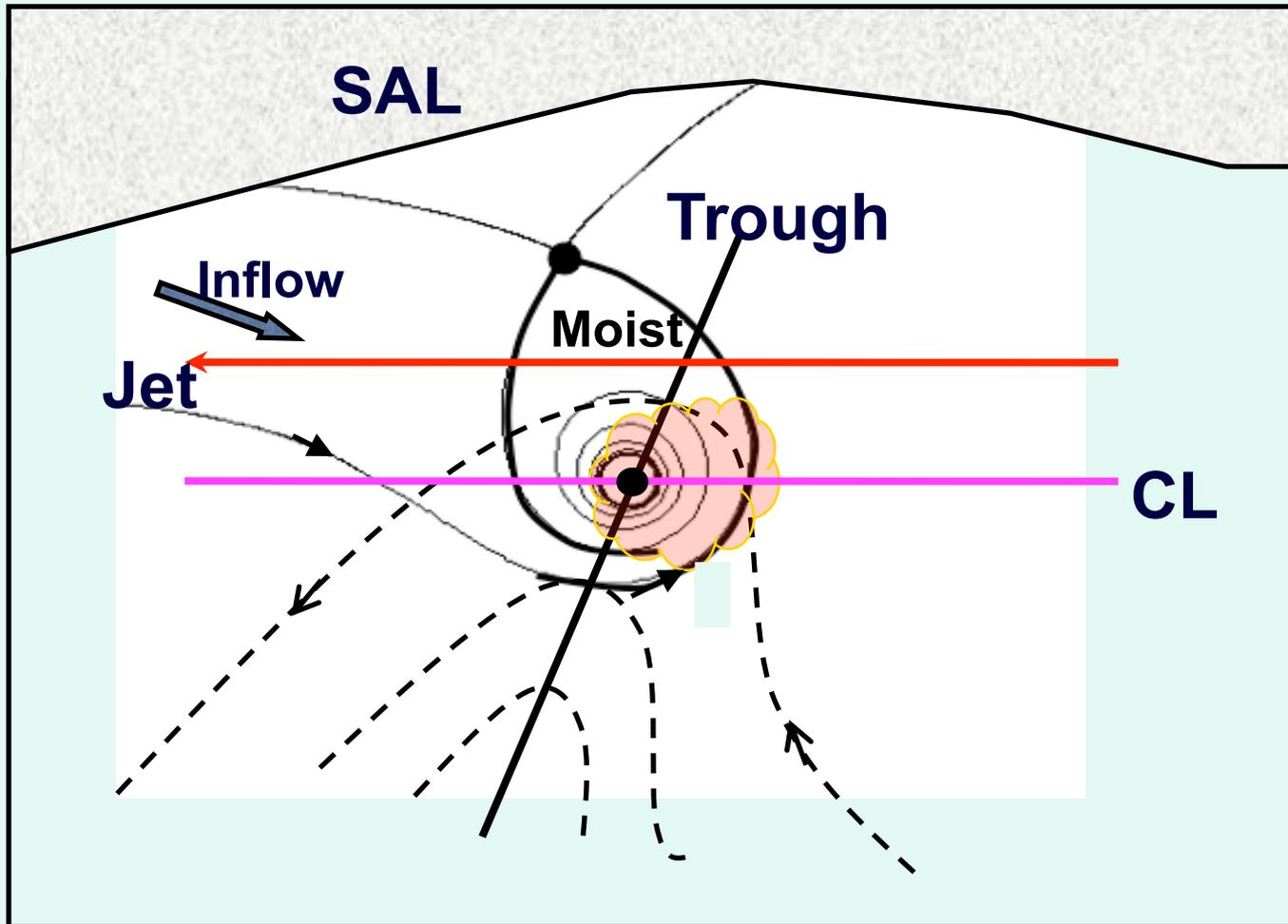
A field study involving 25 flights into Atlantic tropical disturbances tested the principal hypotheses of a new model of tropical cyclogenesis, known as the marsupial paradigm.

**A** longstanding challenge for hurricane forecasters, theoreticians, and numerical weather forecast systems is to distinguish tropical waves that will develop into hurricanes from tropical waves that will not. While tropical easterly waves occur frequently over the Atlantic and east Pacific, only a small fraction of these waves (~20%; e.g., Frank 1970) evolve into tropical storms when averaged over the hurricane season. The problem was insightfully summarized by Gray (1998): “It seems unlikely that the formation of tropical cyclones will be adequately understood until we more thoroughly document the physical differences between those systems which develop into tropical cyclones from those prominent tropical disturbances which have a favorable climatological and synoptic environment, look very much like they will develop but still do not.”

The formation of tropical cyclones (TCs) is one of

at understanding the science of tropical cyclone formation. These include the National Aeronautics and Space Administration (NASA) Tropical Cloud Systems and Processes (TCSP) experiment in 2005 (Halverson et al. 2007), the NASA African Multi-Disciplinary Monsoon Analyses (NAMMA) project in 2006 (Zipser et al. 2009), and the Tropical Cyclone Structure experiment in 2008 (TCS-08; Elsberry and Harr 2008). Adding the results of earlier efforts such as the Tropical Experiment in Mexico (TEXMEX; Bister and Emanuel 1997; Raymond et al. 1998) and even serendipitous observations of the early intensification of Hurricane Ophelia in the Hurricane Rainband and Intensity Change Experiment (RAINEX; Houze et al. 2006), and occasional observations from reconnaissance aircraft (Reasor et al. 2005), we have a collection of studies that have sampled pieces of a large and complex scientific puzzle. However, with the exception of the TCS08

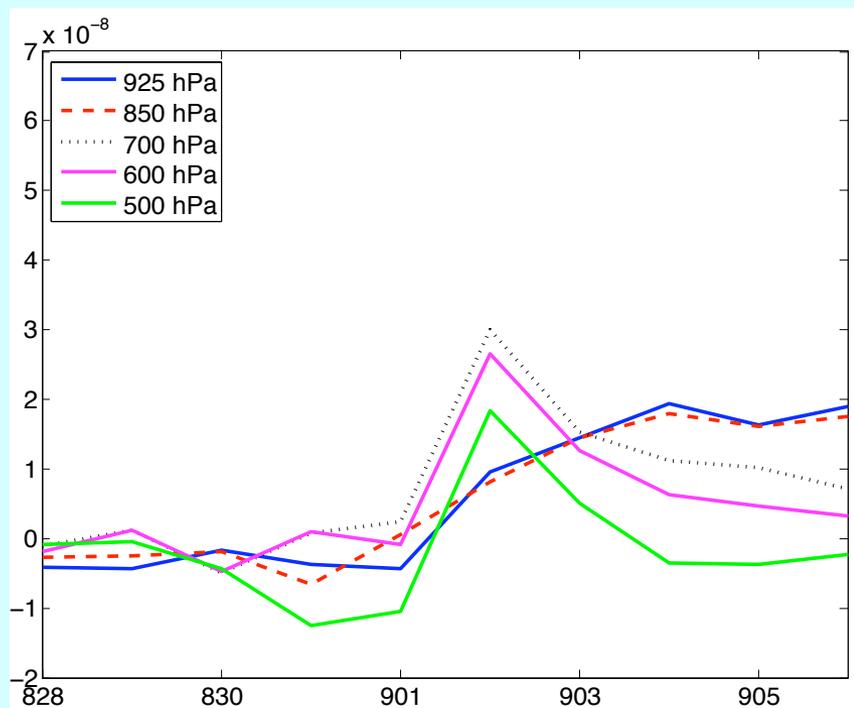
# Old and New Flow Geometry



# Ex-Gaston

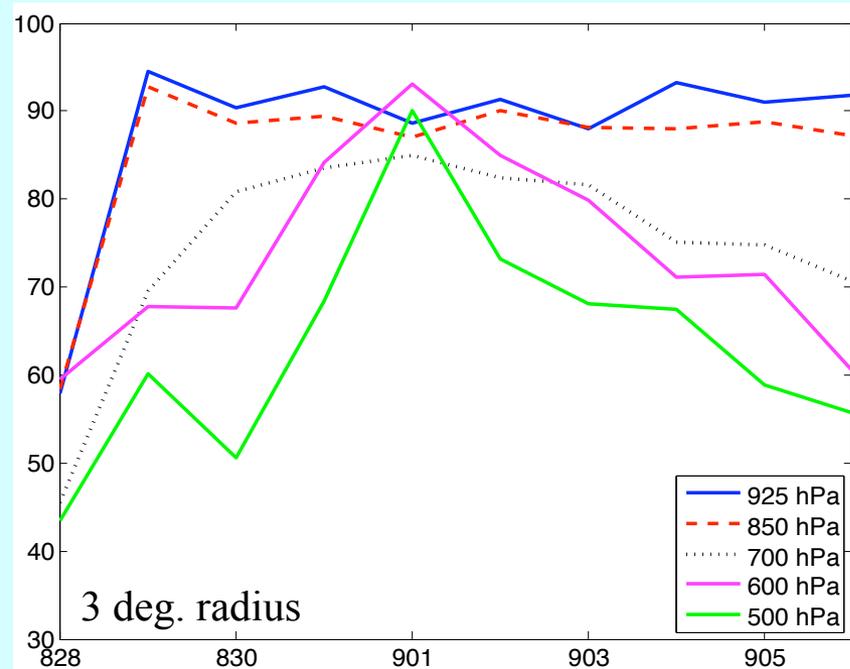
## Pouch-averaged time series

### Pouch-averaged OW ( $s^{-2}$ )



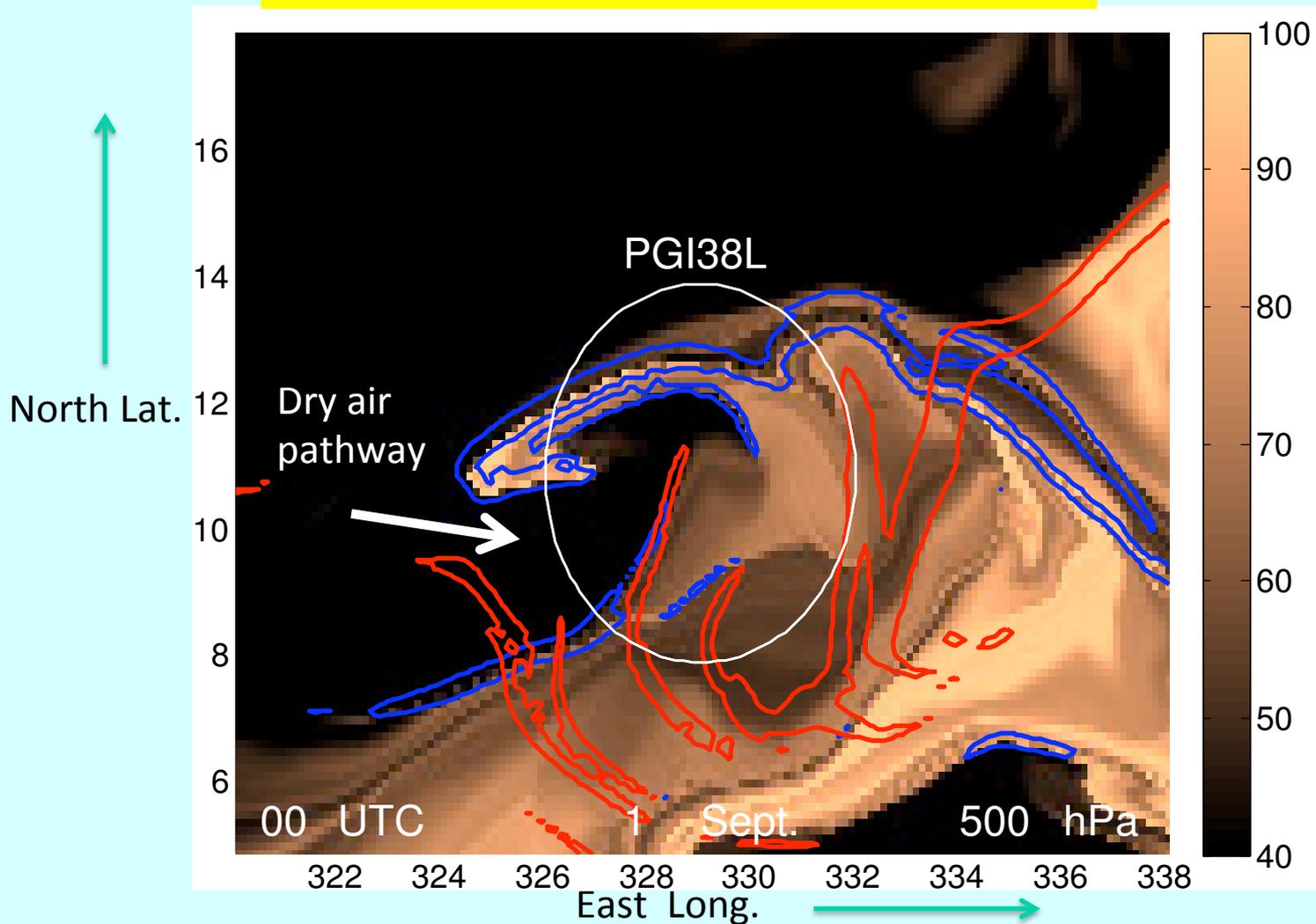
Date

### Pouch-averaged RH



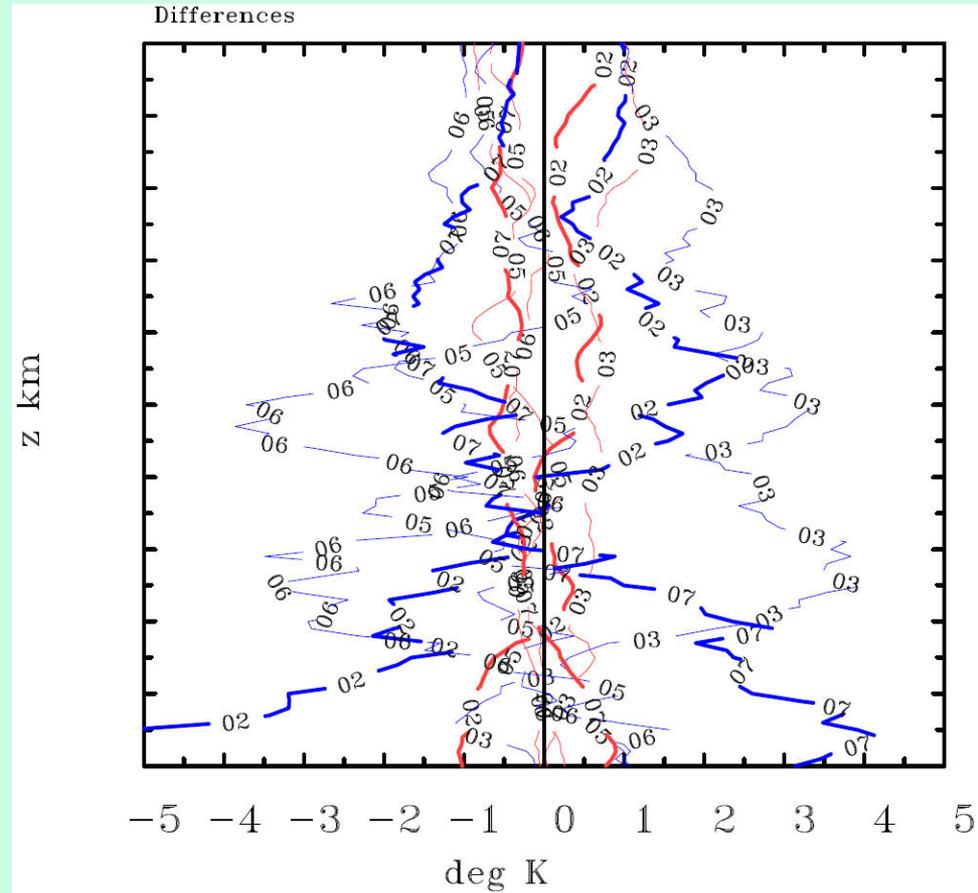
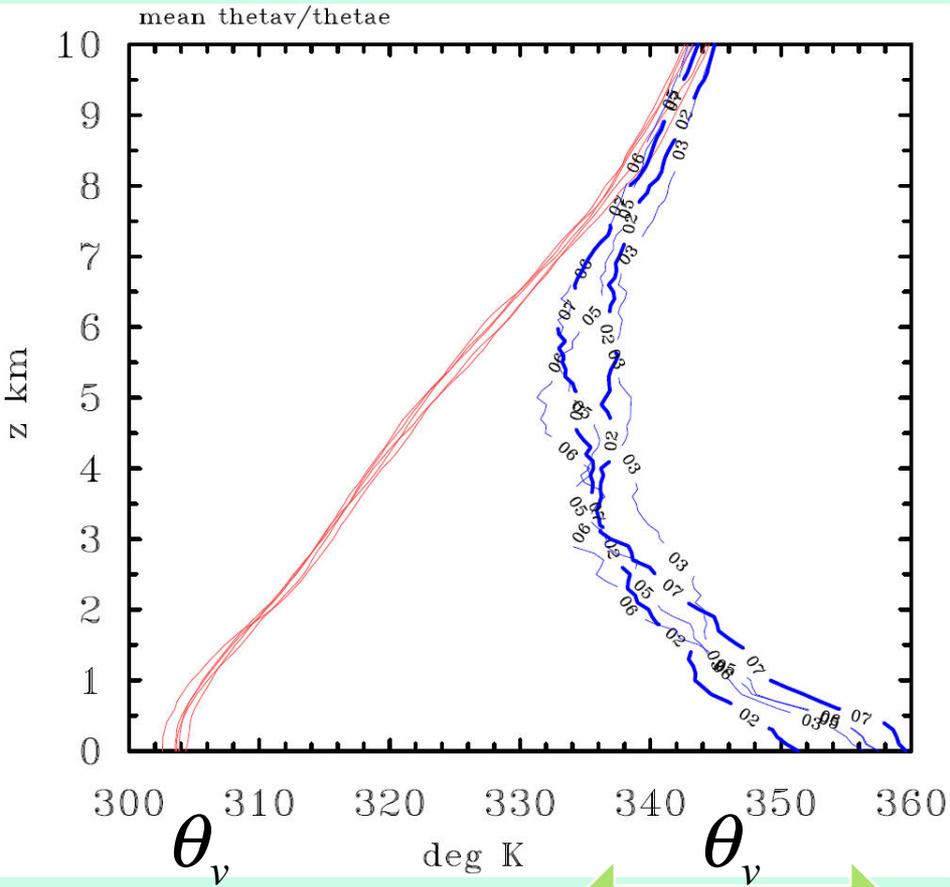
Date

# ex-Gaston (PGI38L) 1 Sept, 0 UTC, 500 hPa



RH tracer field at 500 hPa with LCSs overlaid. Dry air enters the pouch through the opening in the LCS. Red and blue contours mark repelling and attracting LCSs, respectively. [Rutherford and Montgomery, 2011, Atmos. Chem. Phys. Discuss.](#)

# PGI38L (ex-GASTON)



~25 K

# Observations of the convective environment in developing and non-developing tropical disturbances

Roger K. Smith<sup>a 1</sup> and Michael T. Montgomery<sup>b</sup>

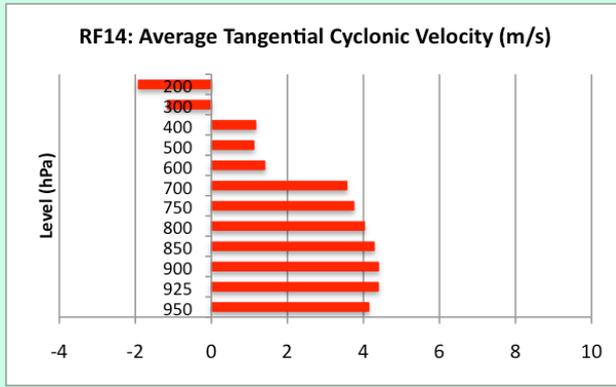
<sup>a</sup> *Meteorological Institute, University of Munich, Munich, Germany*

<sup>b</sup> *Dept. of Meteorology, Naval Postgraduate School, Monterey, CA & NOAA's Hurricane Research Division, Miami, FL, USA.*

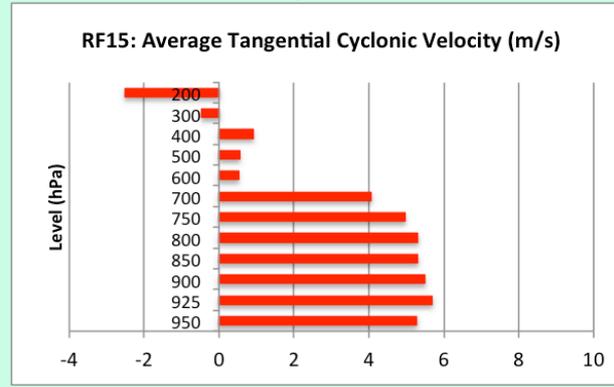
- The most prominent difference *in the thermodynamics* between the non-developing system and the two systems that developed was the much larger reduction of  $\theta_e$  between the surface and a height of 3 km, typically 25 K in the non-developing system, compared with only 17 K in the systems that developed.
- Conventional wisdom would suggest that, for this reason, the convective downdraughts would be stronger in the non-developing system and would thereby act to suppress the development.
- Here we invoke an alternative hypothesis that the drier mid-level air weakens the convective updraughts and thereby weakens the amplification of system relative vorticity necessary for development.

# Pre-Karl

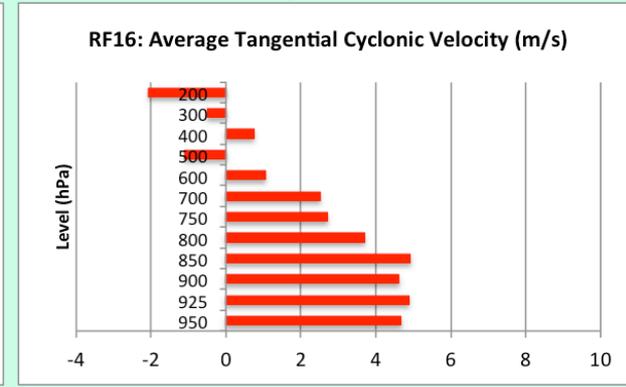
Sept 10



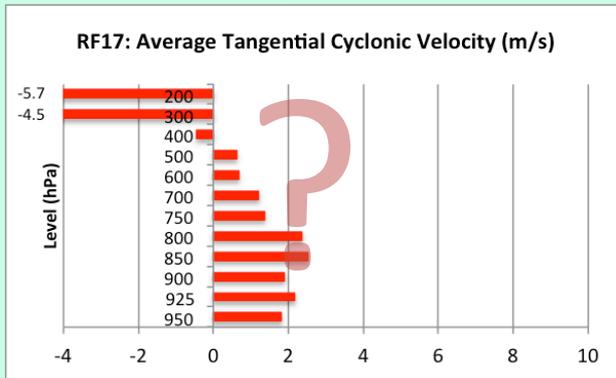
Sept 10



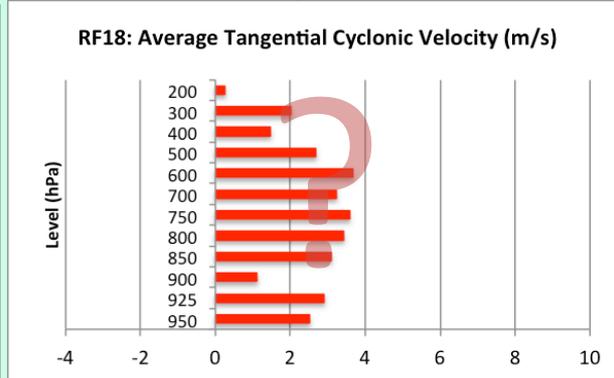
Sept 11



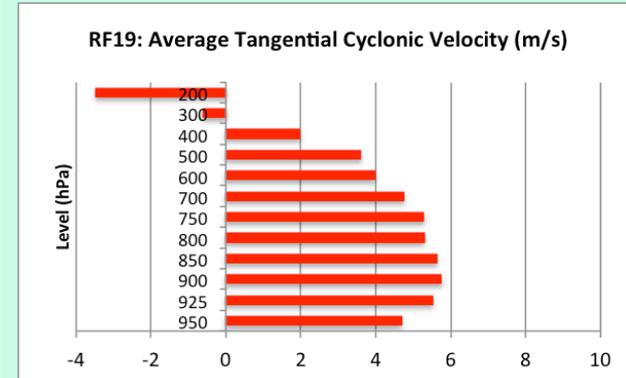
Sept 12



Sept 13



Sept 14



Sept 10 - 1<sup>st</sup> flight

- Cyclonic up to 400 hPa
- Strongest wind below 600 hPa

Sept 10 – 2<sup>nd</sup> flight ... Similar to 1<sup>st</sup> flight, but

- Weak mid-levels became weaker
- Strong low-levels became stronger

Sept 11

- Strongly cyclonic only up to 600 hPa

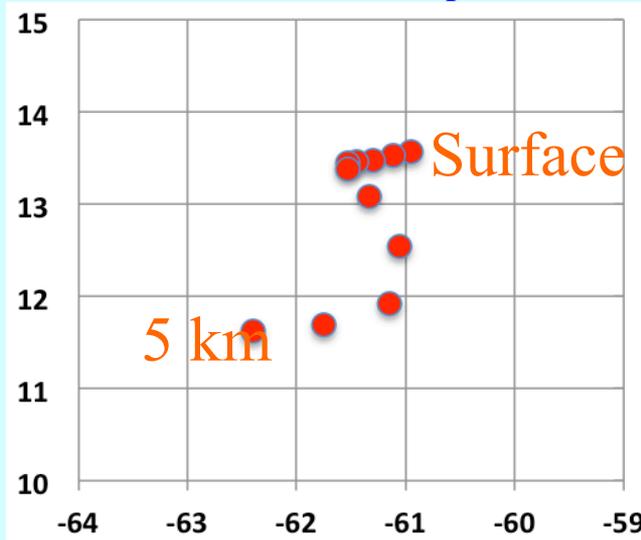
Sept 12-13: Missed portions?

Sept 14 ... Intensifies

- Cyclonic up to 400 hPa
- Wind max at 900 hPa ~5.5 m/s

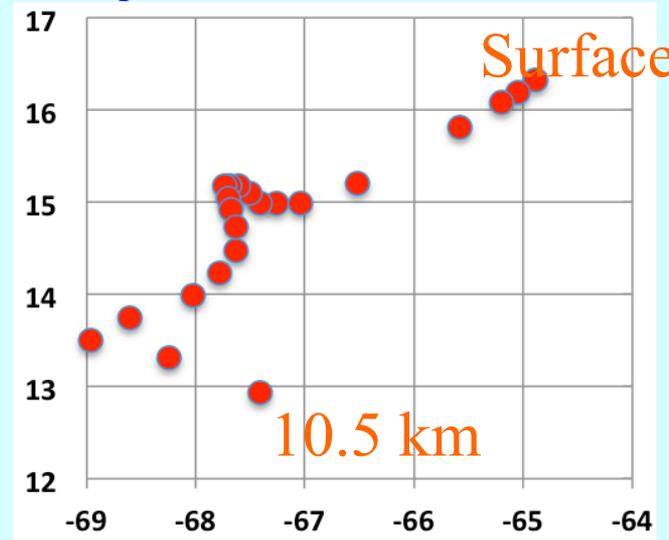
# Pre-Karl

Sept 10 – Convection around center

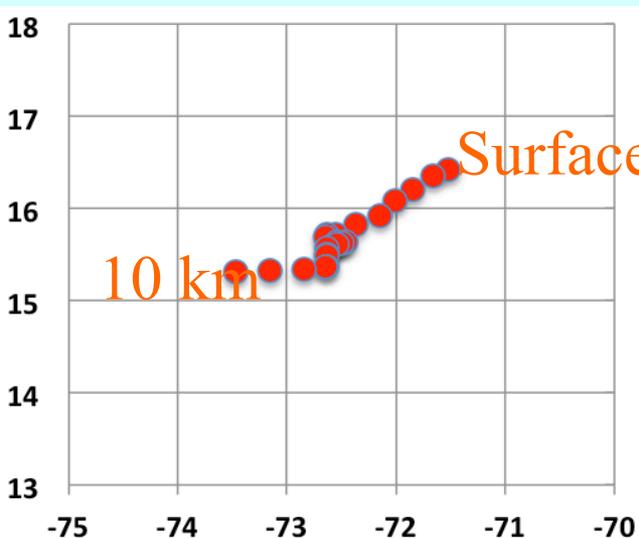


Sept 10 – Convection weakening

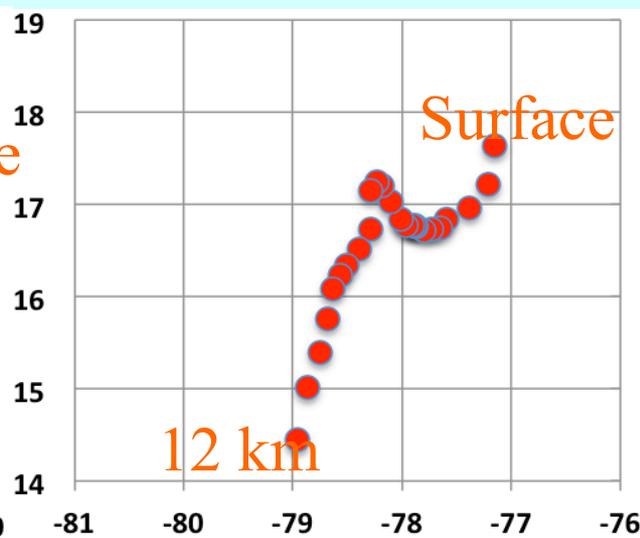
Sept 11 – Convection near center



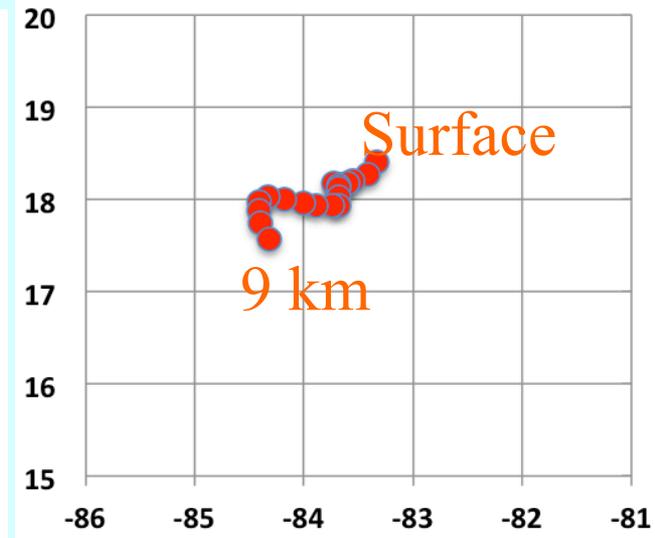
Sept 12 – Convection to north



Sept 13 – Convection to north & west



Sept 14 – Convection close to center



# PREDICT Fact Summary

- Ex-Gaston (Non-developer)
  - Easterly shear knocked the top off the system with dry\* air \*(not shown)
    - Eroded the circulation
    - Inhibited convection
- Pre-Karl
  - Through multiple convective cycles, mid-level circulation was weak, but low-level circulation maintained itself
  - Highly misaligned initially (southwestward tilt), but eventually became vertically aligned
- Pre-Matthew
  - Deep cyclonic layer (surface-400 hPa) steadily becomes more cyclonic over three days

# A numerical study of rotating convection during tropical cyclogenesis

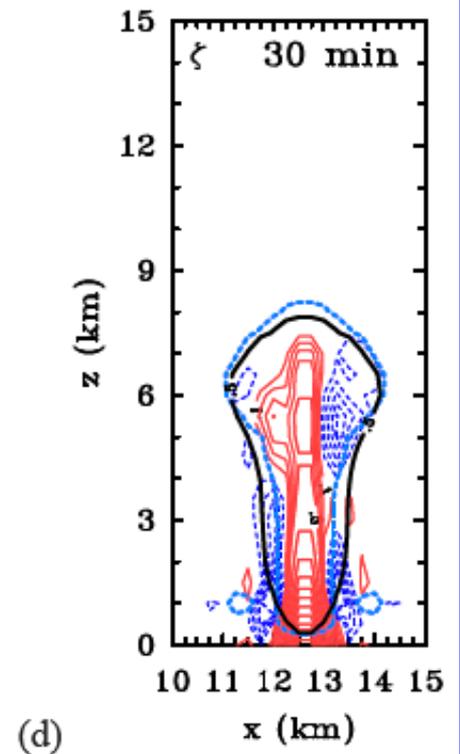
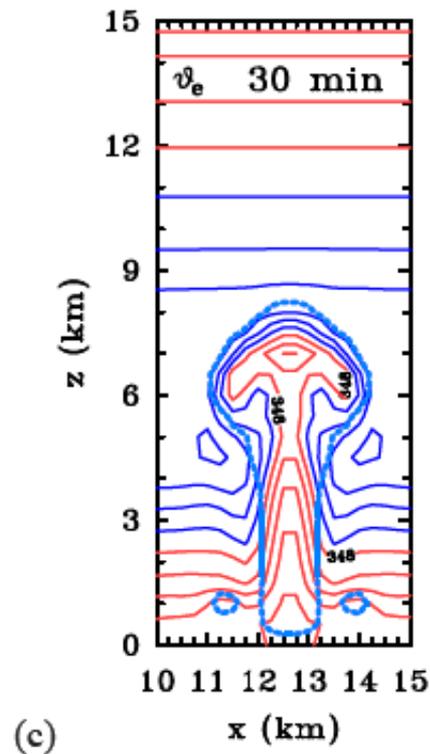
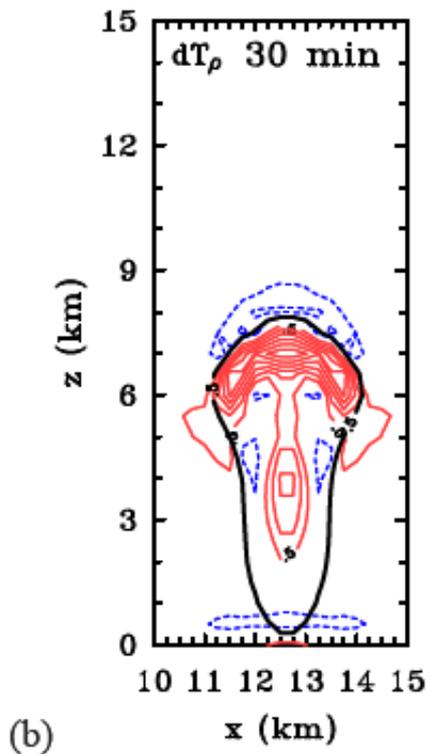
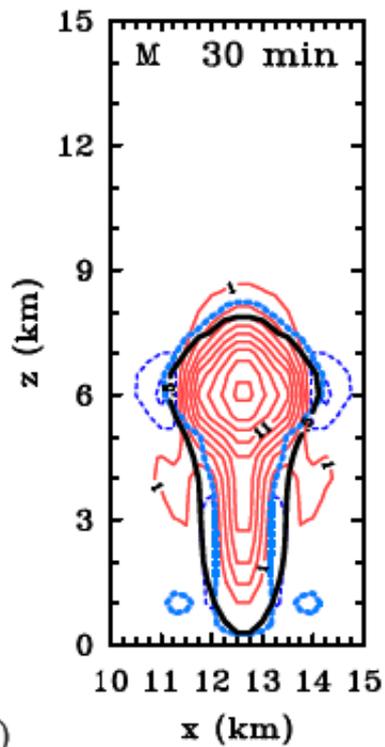
Gerard Kilroy and Roger K. Smith \*

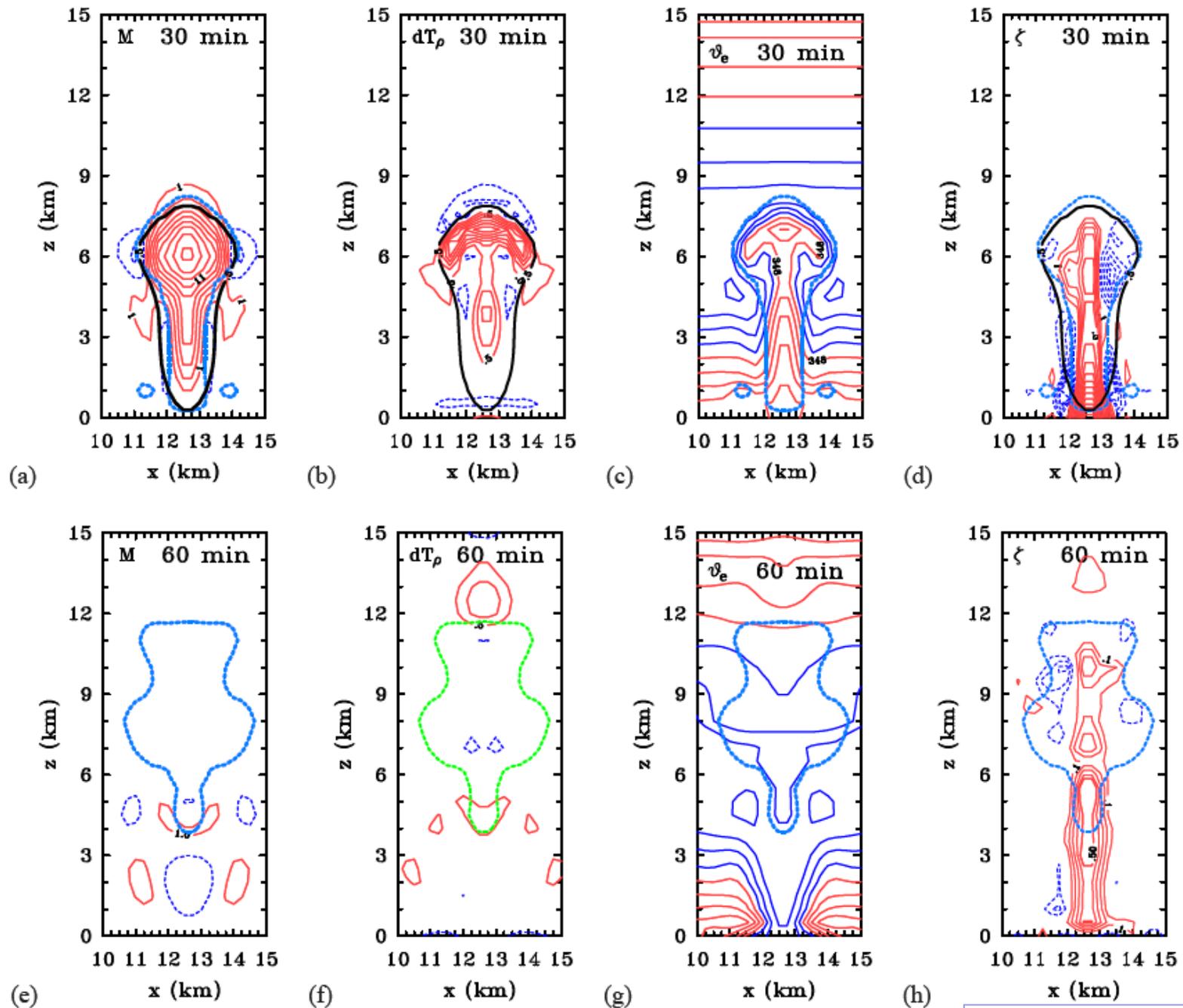
*Meteorological Institute, University of Munich, Munich, Germany*

\*Correspondence to: Roger K. Smith, Meteorological Institute, University of Munich, Theresienstr. 37, 80333 Munich, Germany, Email: roger.smith@lmu.de

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As in recent calculations of Wissmeier and Smith, the growing convective cells amplify locally the ambient rotation at low levels by more than an order of magnitude and this vorticity, which is produced by the stretching of existing ambient vorticity, persists long after the initial updraught has decayed. Moreover, significant amplification of vorticity occurs even for clouds of only moderate vertical extent. The maximum amplification of vorticity is relatively insensitive to the maximum updraught strength, or the height at which it occurs, and it is not unduly affected by the presence of dry air aloft. Thus the presence of dry air is not detrimental to the amplification of low-level vorticity, although it reduces the depth through which ambient vorticity is enhanced.





# Insights from PREDICT/GRIP => HS3 ??

1. New cyclogenesis paradigm helps synthesize multi-scale observations and predicts new properties of the formation process.
2. Data and analyses confirm predicted convective organization at the sweet spot of the parent wave-pouch disturbance.
3. Pouch-averaged view offers a picture of the basic thermodynamic environment within which cyclogenesis takes place. Pouch-averaged view does not support prior hypotheses on thermodynamic environment.
4. Data and analyses suggest alternative view on role of dry air in limiting vorticity amplification on convective scale over pouch depth.

**For HS3: Apply same diagnostic tools and develop new ones also!**



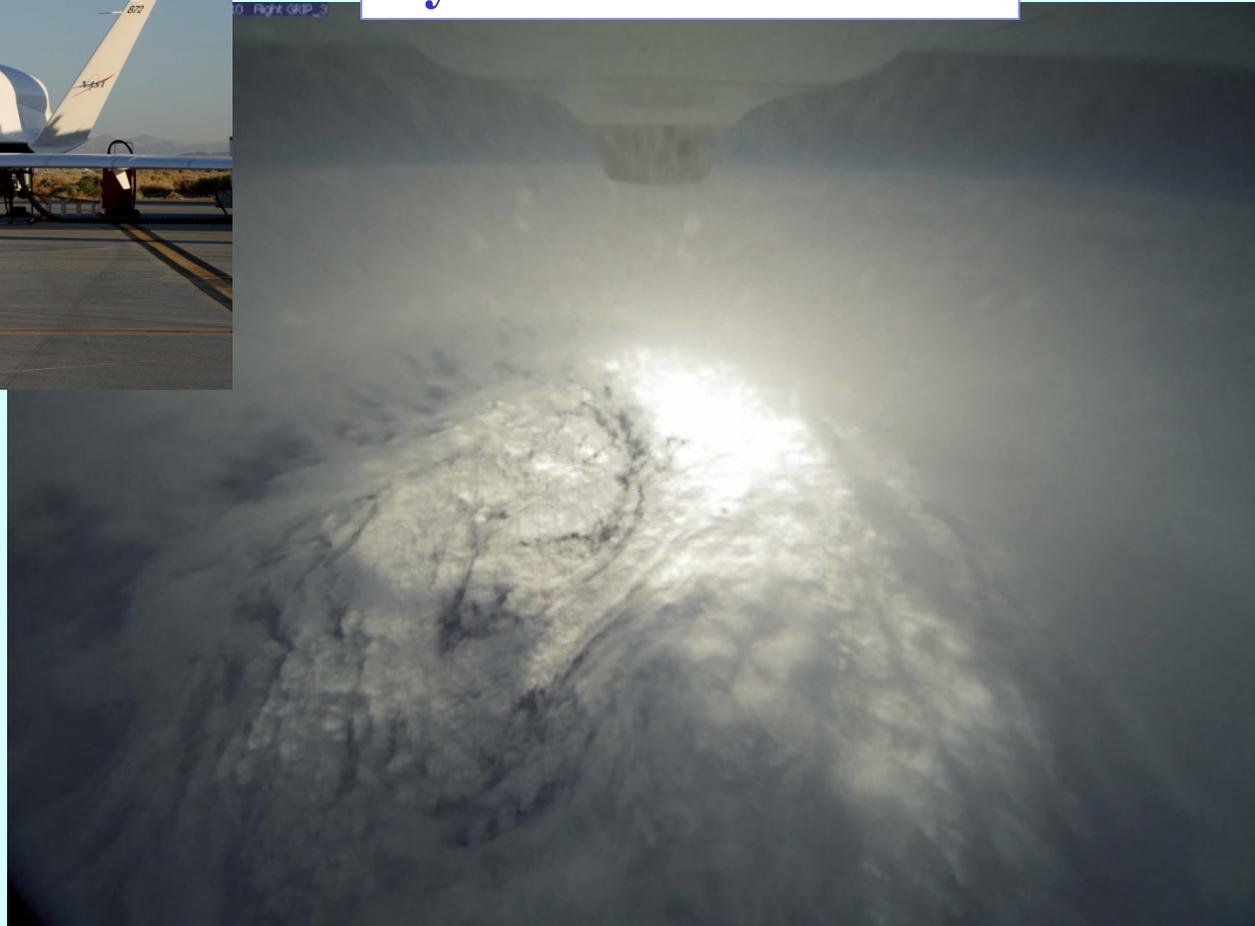
# HS3 2011 Dry Run Wave-Pouch tracking

- 5 July – 18 October
- 41 pouches
  - 20 official invests +
    - 12 Tropical Depressions +
    - 1<sup>st</sup> Pouch forecast lead time before 1<sup>st</sup> NHC warning:  
Average 5 days

# Outlook: future studies using the NASA Global Hawk



## Eye of Hurricane Earl



**End of Presentation**

**Thank you!**